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SIMULATION OF GROUND MOTIONS FROM THE 1971 SAN FERNANDO EARTHQUAKE AND AN AFTERSHOCK OF THE 1975 OROVILLE EARTHQUAKE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this report, we describe a model for earthquakes which can be used to calculate ground motions at the earth's surface cheaply and accurately. The method was developed to be used as input to computer programs which can predict atmospheric pressure waves due to earthquakes. The mothod was used in a previous report to model the 1971 San Fernando earthquake. Approximations used in that work are checked in this report using more exact methods. The model is then modified to fit observations of an aftershock of the 1975 Oroville earthquake.

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I. INTRODUCTION

In this report, we address the calculation of ground motions from earthquakes which are to be used to drive programs which compute atmospheric pressure waves due to the earthquakes. In particular, we examine the approximations made by Bache, et al. (1981) used to formulate a model for the San Fernando earthquake. These approximations allow the ground motions to be computed economically on a dense grid on the free surface. The free surface motions are required by the atmospheric propagation codes used by Mission Research Corporation who will conduct that part of the program. The approximate solutions were checked against exact solutions and found to be good for these purposes. These results are the subject of Section II.

The parameters of this source model were then changed to provide a means for computing the ground motions of a much smaller event-an aftershock ($M_L = 4.6$) of the 1975 Oroville earthquake. This event was chosen because strong-motion accelerograph data were recorded and because these were several previous studies of the event. Comparisons of the synthetic seismograms from our model with observations and the modeling study of Boatwright (1981) are shown in Section III.

II. SOURCE AND PROPAGATION MODEL FOR THE SAN FERNANDO EARTHQUAKE

Bache, et al. (1981) described an inexpensive method for modelling ground motions at the free surface above the 1971 San Fernando earthquake. These ground motion calculations are to serve as input to programs which propagate the induced atmospheric pressure wave to the ionosphere. The atmospheric propagation is to be done by Mission Research Corporation (MRC). To achieve economy in the ground motion calculations, various approximations to the source and to the propagation models were made. The purpose of this section is to investigate the validity of the assumptions by comparing synthetic seismograms generated using these approximate methods with more exact methods. We find that the approximations do not significantly degrade the results.

We divide the approximations into two groups: those associated with the source and those related to the propagation. The eartnquake model is based on the crack model of Sato and Hirasawa (1973). The singularities in acceleration due to abrupt stopping phases have been replaced with boxcar smoothing functions. The D-model of Boatwright (1980) is used to determine the amplitude and duration of the boxcars. As discussed in Bache, et al. (1981), this model or ones quite similar to it generate seismic radiation which fit observations over a broad frequency band in the near-field and the far-field. In other words, when the propagation is done correctly, the model fits the data and is probably about the best we can do.

The formulation used for radiation from the Sato and Hirasawa model is that for a homogeneous whole-space with receivers in the far-field. The solution is far-field in the sense that geometric spreading is the same from all parts of the fault. The finiteness of the fault is manifested only in the time history. The effects of the free surface are then approximated using a frequency-independent reflection coefficient. In the following, we examine these two approximations.

The far-field or point source representation appears safe due to the nature of the San Fernando event. The data are best fit by discrete, localized events which dominate the seismograms (e.g., Bache and Barker, 1978). The radiation from the initial deep event, for example, is dominated by faulting over a scale of about 1 to 2 km.

The effects of free surface can be rigorously included only by computing the response using a frequency dependent reflection coefficient. Mathematically, this can be formulated as follows. In the Laplace frequency - ray parameter domain (as is used in the Cagniard-de Hoop method), the displacement at the free surface may be written as

$$u(s) = \frac{2}{\pi} S(s) s \, \mathrm{Im} \int_0^{i\infty} E(p) K_\nu(spr) e^{-s\eta h} R(p) \, dp \qquad (1)$$

where S is Laplace frequency

p is ray parameter

E(p) is the earthquake radiation pattern

L is the source depth

r is range

η is the vertical slowness

R(p) is the free surface reflection coeffient

K_ν is a modified Bessel function

S(s) is the source spectrum, and

Im denotes the imaginary part.

This equation may be evaluated by the usual Cagniard approach (Barker and Minster, 1980) or may be approximated as in Bache, et al. (1981) by the saddle-point method. That is, we approximate the expression with its value at the geometric travel time t_0 and ray parameter p_0. Thus, for subcritical arrivals ($p_0 < 1/\beta$),

$$u(t) = \frac{2}{\pi} S(t)\ E(p_0)\ \text{Real}\ (R(p_0))\ \frac{H(t-t_0)}{\sqrt{r^2 + h^2}} \quad (2)$$

and for post-critical arrivals ($p_0 > 1/\beta$),

$$u(t) = \frac{-2}{\pi} S(t)\ E(p_0)\ \text{Im}\ (R(p_0))\ \ln \frac{|t_0-t|}{2t_0} \frac{1}{\sqrt{r^2 + h^2}} \quad (3)$$

(Mellman and Helmberger, 1978). These are essentially the expressions evaluated by SFVERT described in Bache, et al. (1981).

Equations (2) and (3) may be inaccurate representations of the full integral (1) when

1) the periods of interest are of the same order or greater than the travel time, or

2) the Rayleigh wave is an important contribution (Equations (2) and (3), of course, completely ignore the Rayleigh wave).

To quantify the errors introduced by using (2) and (3), we have compared ground motions and atmospheric pressure pulses using (2) and (3) and the exact representation (1). To compute the solutions for the Sato and Hirasawa source, we used the formulation for a dislocation given by Barker and Minster (1980) with the substitution

$$\mathring{M}_0 = I_\alpha$$

where I_α is given by Equation 7.1, Bache, et al. (1981).

Figures 1 and 2 show two comparisons: one where the range is held fixed and the azimuth varied and one where the range changes while the azimuth remains constant. Although the solutions do not overlay, the important features, pulse duration and amplitude, agree well except at a range of 5 km (Figure 2). The discrepancy at 5 km is due to near-field effects. The differences at farther ranges are

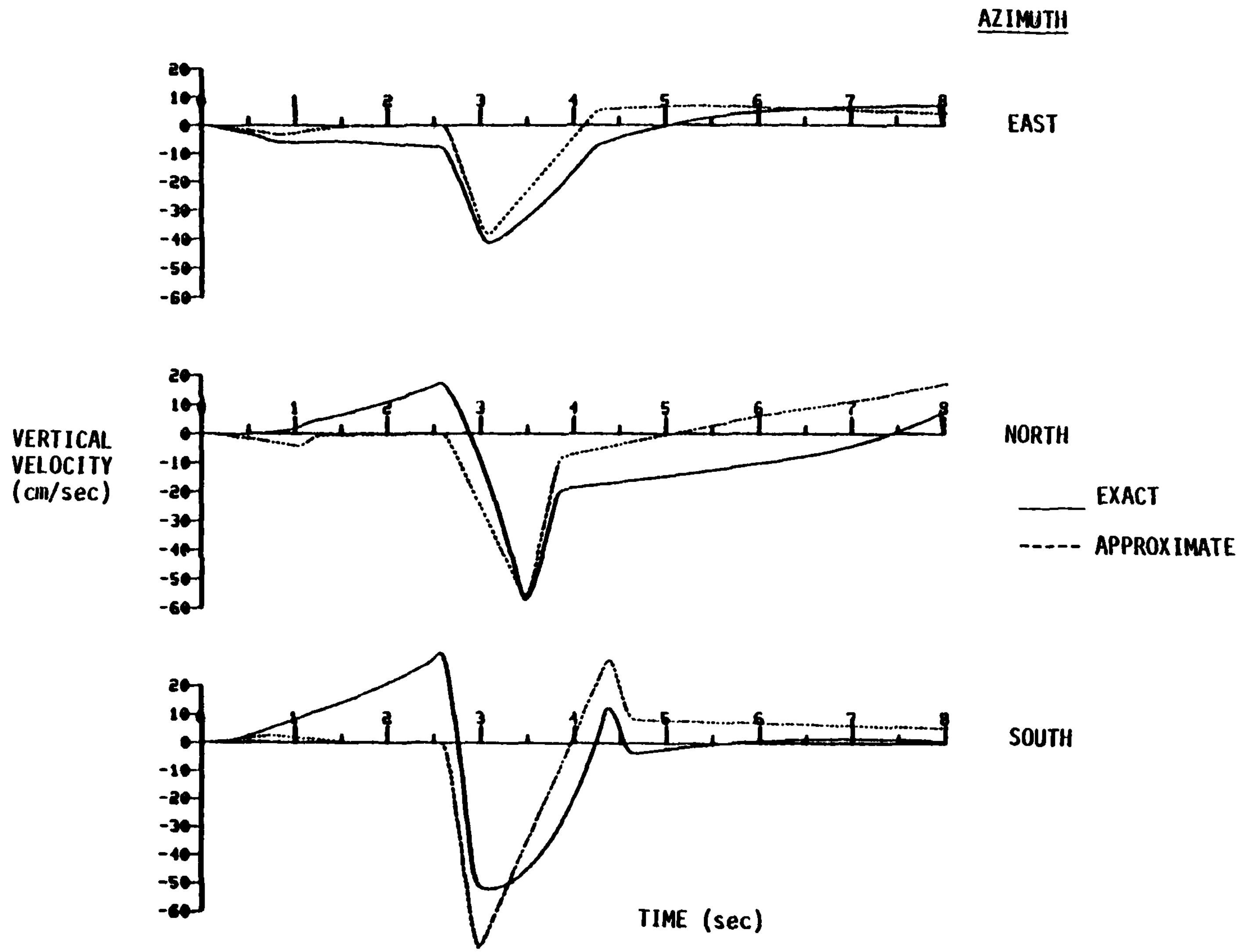

Figure 1. Synthetic velocity seismograms at a range of 13 km are compared.

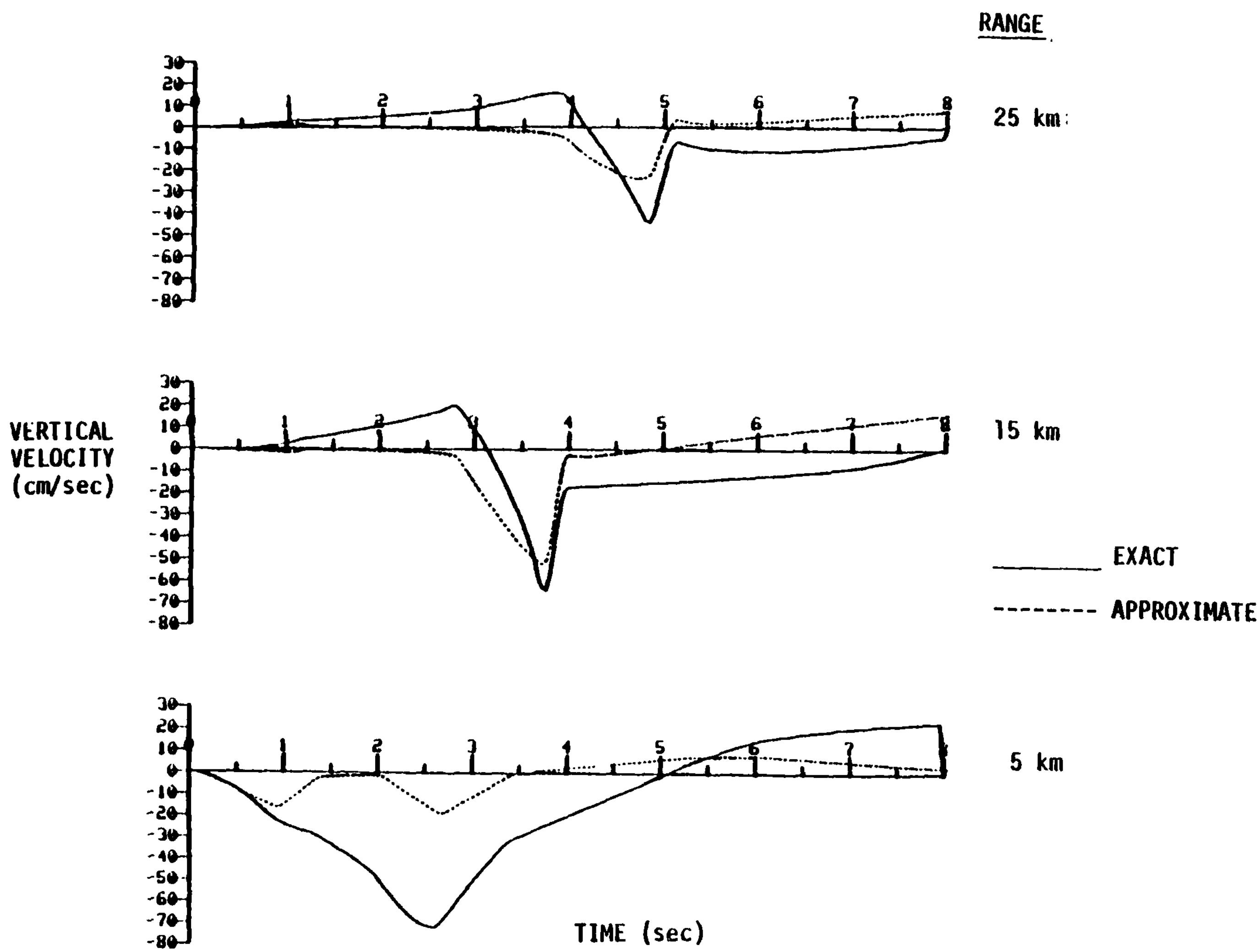

Figure 2. Synthetic velocity seismograms at an azimuth of 15^0 are compared.

due to the reflection coefficients used in the two calculations. This can be seen by examining exact Cagniard-de Hoop solutions and the approximate solutions for a whole-space. These comparisons have not been shown here.

A more important check is to compare the approximate solutions propagated into the atmosphere by MRC (Wortman, 1981) with calculations using the exact formulation. The comparisons are made at a height of 40 km above the ground. The solutions are compared at a range of 15 km at three azimuths in Figure 3. In Figure 4, the solutions along a southern azimuth are shown at ranges of 15, 30, and 40 km. Even at 40 km, where the Rayleigh wave might be important, the agreement is good.

Although the approximate solutions contain many approximations, they may be used to predict atmospheric pulse durations, shape and amplitudes. Details of the pulse are not represented but are excusable in light of the simplifications in geology and fault model.

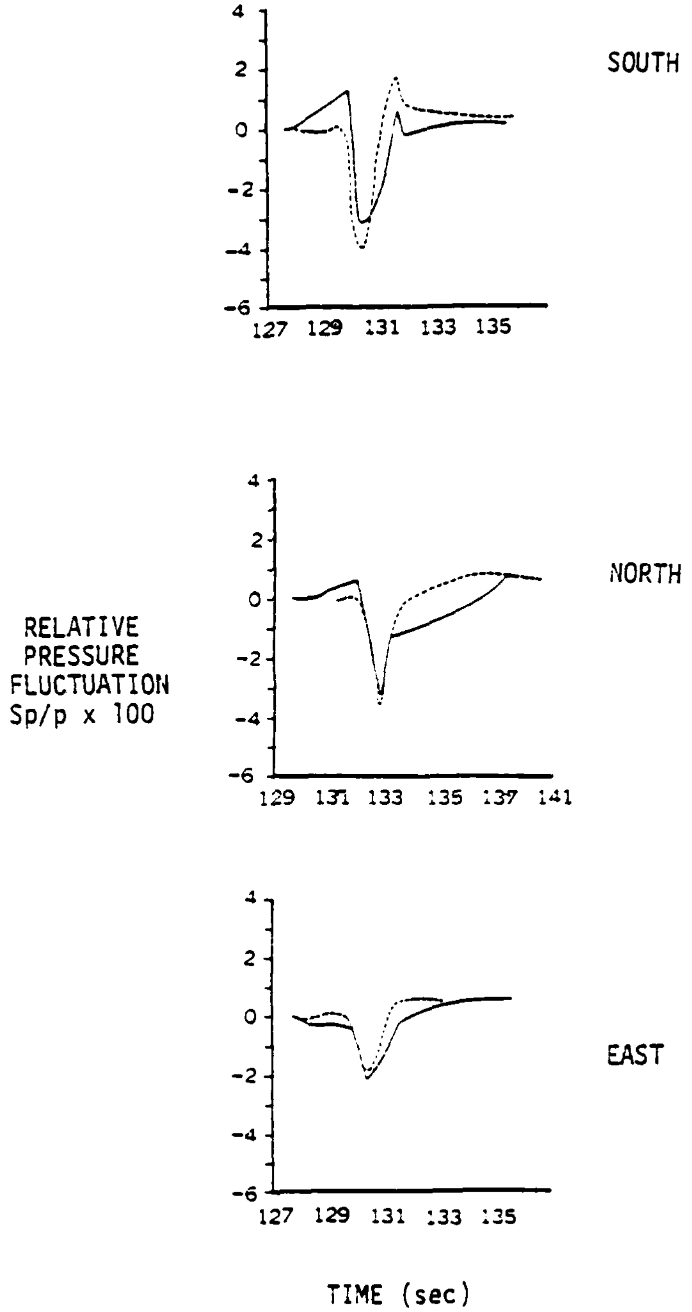

Figure 3. Pressure pulses from Source 1 at three ranges at a height of 50 km and range of 15 km are shown. Solid lines are solutions using exact Cagniard-de Hoop formulation. Dashed lines are from propagating approximate solutions (Figure 15, Wortman, 1981).

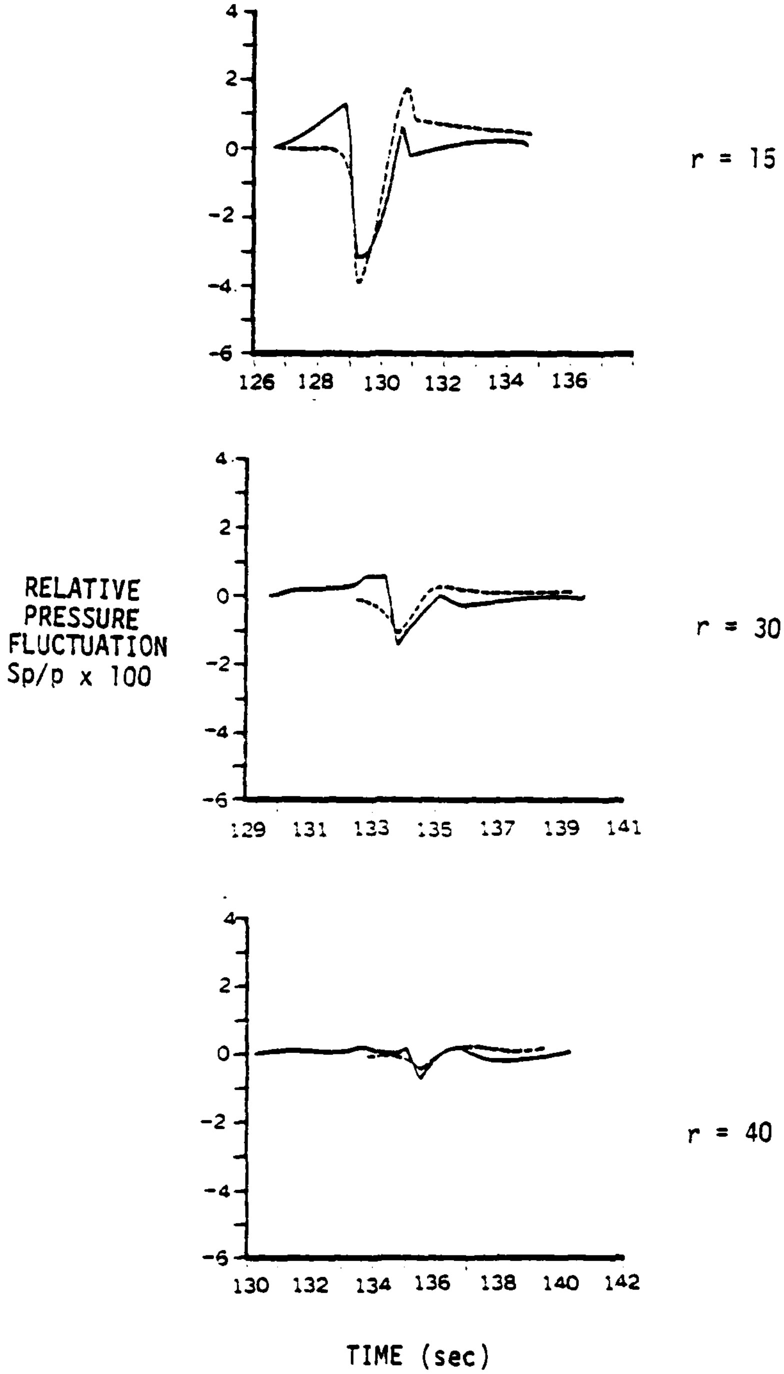

Figure 4. Pressure pulses from Source 1 due south of the origin for three ranges are shown. Solid lines are solutions using exact Cagniard-de Hoop formulation. Dashed lines are from propagating approximate solutions to a height of 40 km (Figure 16, Wortman, 1981).

III. A MODEL FOR AN AFTERSHOCK OF THE 1975 OROVILLE, CALIFORNIA EARTHQUAKE

The modified Sato and Hirasawa model described in Bache, et al., (1981) was shown to agree with the observations of the San Fernando Earthquake. Its implementation was shown in the previous section to be a good approximation for atmospheric/ground motion coupling calculations. In the following, we show how the parameters of this model can be modified to provide a suitable model for the aftershock occurring at 0103 hours on 3 August 1975. Its local magnitude was $M_L = 4.6$.

Our approach is to match the parameters of our model with those of Boatwright (1981), who derived a model based on observations of first motions and waveforms at stations within about 10 km of the source. Boatwright's model and ours have many features in common and the correspondence is straightforward. His results are consistent with Langston and Butler (1976), who examined long period teleseismic body waves of the main shock, and with Lahr, et al., (1976), who concentrated on first motions and locations of the entire main event-aftershock sequence.

The modified Sato and Hirasawa model used by Bache, et al. (1981), is parameterized by its orientation (strike, dip, and rake), fault radius L, its initial slip velocity D_0, the rupture velocity V_R, and the parameter γ which is the fraction of the fault radius over which the rupture velocity is constant. For positions on the fault farther than γL from the center, the rupture velocity decays linearly to zero at the edge of the fault. The values of these parameters used in this study are listed in Table 1.

The orientation parameters were taken from Boatwright's upper hemisphere plot of the fault plane solution and refined by personal communication. The fault radius was deduced from Boatwright's estimate of the fault area of 2.3 km^2, and, since Sato's and Hirasawa's fault is circular, $L = 0.86$ km.

Table 1

SOURCE PARAMETERS FOR THE 0103
OROVILLE AFTERSHOCK

Strike (Deg)	180
Dip (Deg)	65
Rake (Deg)	-70
Depth (km)	8.8
Fault Radius (km)	0.86
Fraction of radius for which rupture is uniform	0.70
Rupture Velocity (km/sec)	3.1
Slip Velocity (cm/sec)	150

The rupture velocity was found directly by Boatwright. The initial slip velocity was computed from Equation (19) of Boatwright (1980), which is taken from Dahlen (1974),

$$\dot{D}_o = C(\frac{V_r}{\beta}) \frac{\tau_e V_r}{\mu} \quad ,$$

where μ is the shear modulus, $C(v_R/\beta)$ is the Kostrov function and τ_e is the dynamic stress drop. Boatwright (1981) finds $\tau_e = 214$ bars and V_R/β to be 0.85 which, for a circular fault, implies a value of $C = 0.8$.

The parameter γ was deduced from Boatwright's observation that the healing interval in his model was 0.2 sec. The relationship between γ and this interval is given by Boatwright (1980), quation (18) as

$$\Delta t_H = \frac{L}{V_R} (\gamma^{-1} - \gamma)$$

which has the solution

$$\gamma = \frac{1}{2} [-\nu + \sqrt{\nu^2 + 4}]$$

where

$$\nu = \frac{V_R}{L} \Delta t_H \quad .$$

We have compared our radial velocity seismograms at six sites with the solutions of Boatwright and with the observed strong motion records as shown by Boatwright. The station positions relative to the epicenter are tabulated in Table 2. The seismograms are shown in Figure 5. The records are dominated by a pulse-like shear arrival which are characterized by a sharp positive arrival with a lower frequency negative tail. This shape is matched well by ours and Boatwright's synthetic seismograms at all stations except OMC. WE have been unable to match this seismogram by a trial-and-error search through the space of fault orientations near the one given above. Station OMC is the only station not in the quadrant of the radiation pattern occupied by the other five stations. We consistently find that along ray paths near that going to OMC, the shear arrival is very small. This is not the case for the data tnere. However, the remaining stations fit rather well indicating that the frequency content and scaling factors (e.g., slip velocity) are correct.

Table 2

STATION POSITIONS RELATIVE TO EPICENTER
OF 0103 OROVILLE AFTERSHOCK

Station	Range (km)	Azimuth (Deg., E of N)
1	9.2	-134
4	7.6	-120
OAP	7.5	-86
OMC	2.2	-25
EBH	5.3	-160
5	6.5	-141

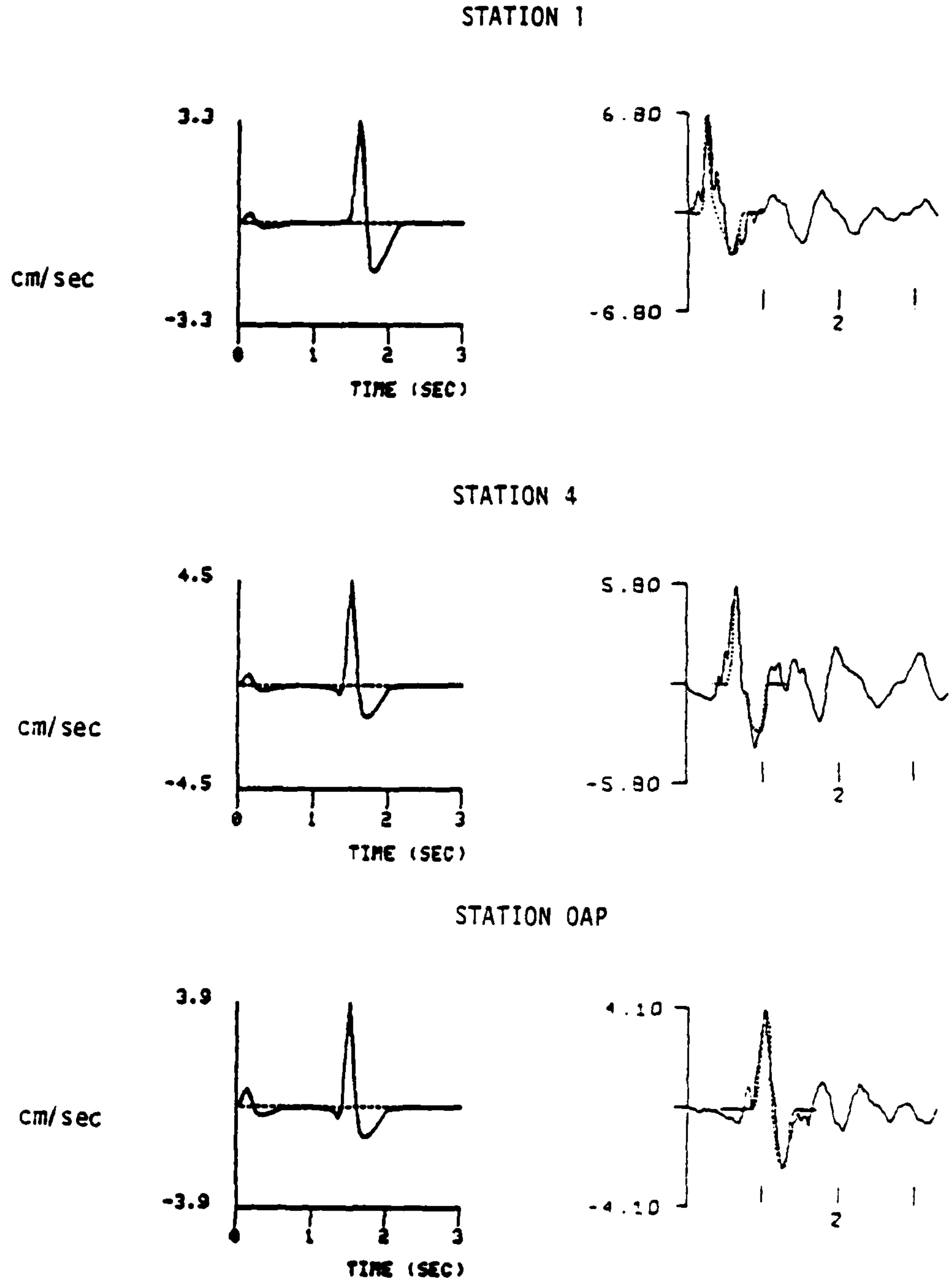

Figure 5. The left column shows the synthetic radial velocity seismograms for the model described in the text. The right column shows the observed seismograms (solid line) and the synthetics from Boatwright (1981) (dashed line). Time is relative to the P-wave arrival in the left column, and relative to the initiation of the strong motion recording on the right. Amplitudes of the synthetics on the left are as indicated. Those on the right have been scaled to the observation.

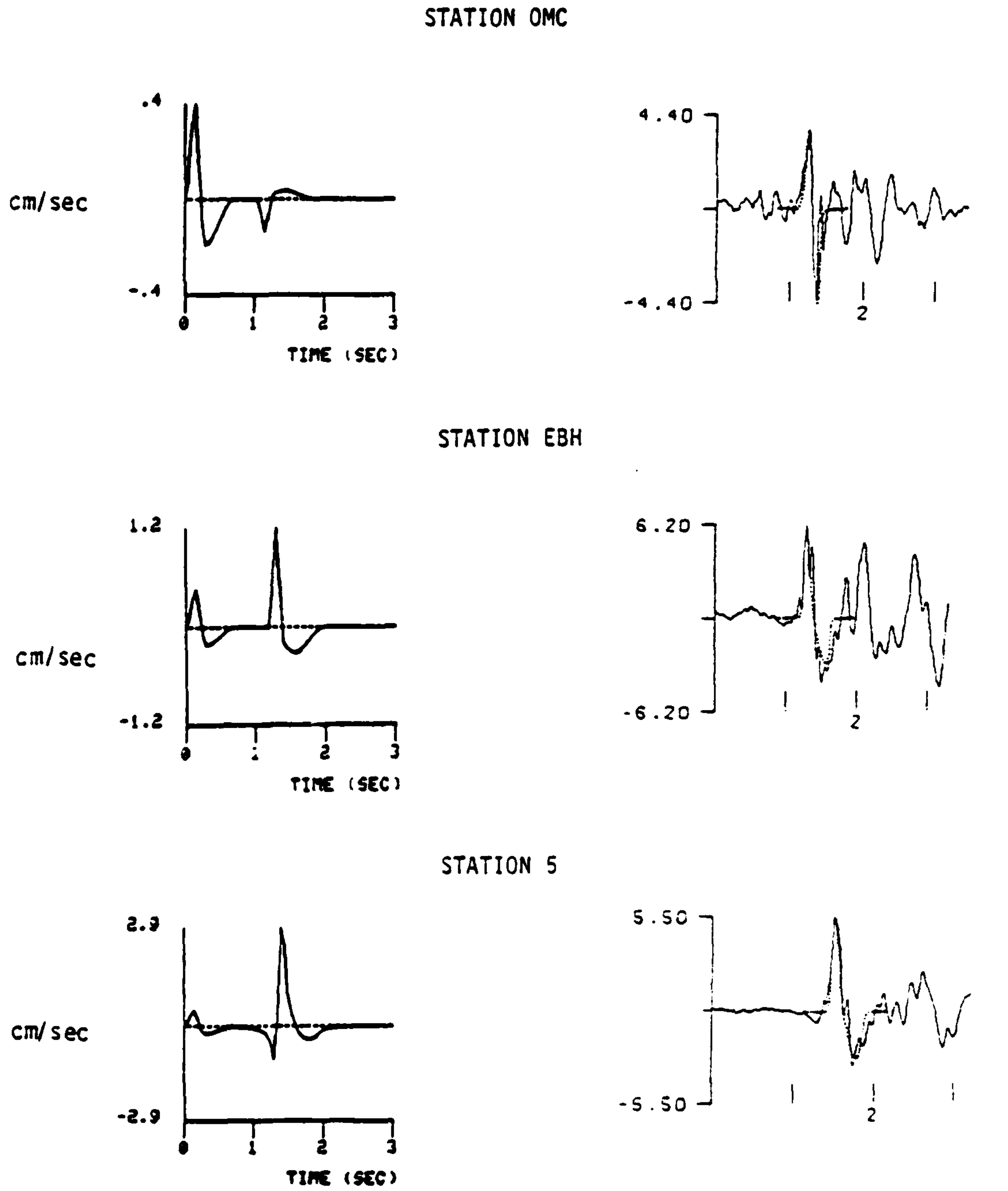

Figure 5. (Continued) The left column shows the synthetic radial velocity seismograms for the modeldescribed in the text. The right column shows the observed seismograms (solid line) and the synthetics from Boatwright (1981) (dashed line). Time is relative to the P-wave arrival in the left column, and relative to the initiation of the strong motion recording on the right. Amplitudes of the synthetics on the left are as indicated. Those on the right have been scaled to the observation.

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